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Jet Penetration of High Explosive

P. Poulsen

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Livermore
National
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Title: Jet Penetration of High Explosive

Author: Dr. Peter Poulsen

Lawrence Livermore National Laboratory, P.O. Box 808, L-099, Livermore, CA 94550

Our present hydrocodes are not able to accurately calculate the penetration of shaped charge jets through thick layers of high explosive (HE). The observed jet erosion is much greater than hydrocode calculations indicate. It appears that the cause of the inaccuracy is the improper calculation of the interaction between the eroded jet material and the incoming unperturbed jet. These two counter-streaming layers interact when back-flowing jet material being forced onto the incoming jet by the pressure in the detonation products. Even 3-D codes are unable to compute the interaction to match the observed behavior. As a consequence a formulation has been developed that is based on momentum exchange between the counter-flowing layers near the tip of the jet. It predicts the length and speed of the perturbed jet and the speed of propagation of the remaining jet. One experimentally determined parameter is included in the equation. The experiments that form the basis for the model are discussed.

ENHANCED JET EROSION IN HIGH EXPLOSIVE

It is found that a transition between two flow patterns takes place in thick HE targets. In this case, the jet will initially propagate into the HE at the same rate as into an inert material of the same density. The part of the jet that has stagnated and is flowing nearly co-axially with the incoming jet (but at a much lower speed) is being forced toward the surface of the incoming jet by the pressure of the reaction products but has not as yet made contact. After it makes contact, both axial and perpendicular momentum transfer takes place between the two jet components. After this transition, a new steady state will develop for the propagating jet, with the unperturbed front of the jet propagating at a slower rate than previously. The perturbed front of the jet is still propagating at or near the original rate, having had relatively little axial momentum exchange. However, it has acquired radial momentum and is spreading out as it is propagating; it is therefore becoming less capable of penetrating downstream targets. It is the unperturbed part of the jet that is capable of penetrating downstream targets. A calculational method for predicting this case is presented below.

The proposed jet erosion treatment was developed after observations of a number of jet / HE erosion experiments and has been successfully used to predict the results of subsequent experiments. In the following, we discuss a series of experiments that were designed to investigate the propagation of jets through HE.

EXPERIMENTS RELATING HE THICKNESS TO JET ATTTENUATION

Experiments were conducted to investigate the jet attenuation as a function of HE thickness; it was of particular interest to quantify the region in which the transition to an anomalously high attenuation rate took place. The experiments were conducted for HE thicknesses of 2, 4, 6, 8, and 10 cm. Each slab of explosive was cylindrical with a diameter of 20 cm. Each slab was also backed with 1.27 cm of steel plate. The explosive was Comp B. The shaped charge was a TOW2A placed at a distance of three charge diameters (CD) from the front surface of the explosive. This distance is 43.8 cm for the TOW2A. Three switches which triggered at jet arrival were placed between the HE and the shaped charge; their signal and their known location was used to determine the velocity of the jet prior to striking the explosive. A secondary target to measure residual jet penetration was placed at a distance of 105 cm. This target consisted of a number of stacked steel cylinders centered on the expected jet path, each 15.2 cm in diameter and 7.6 cm long. A switch was placed in front of each cylinder to measure the time of arrival of the jet. Radiographs of the jet in the region between the HE target and the cylinders were taken at specified times. Usually three radiographs were taken for each shot. The radiographs were used to determine the position and velocity of the tip of the perturbed jet and of the front of the unperturbed part of the jet. The latter velocity is defined as the exit velocity. For uniformly stretching jets, the exit velocity is easily related to the attenuation of the jet, as shown below.

Radiographs of selected shots are shown in figure 1 to illustrate the perturbed and unperturbed parts of the jet. A jet which has passed through an inert metallic target will look similar to that in figure 1a. The jet has been attenuated by the normal process, but is not otherwise perturbed. If the target is a slab of thick HE, there are two parts to the jet, as shown in figure 1b. The first part is highly perturbed and the second part is still solid. The speed of the tip of the perturbed jet is approximately that which would be expected for an inert target having the same thickness and density as the explosive. However, since the perturbed part of the jet

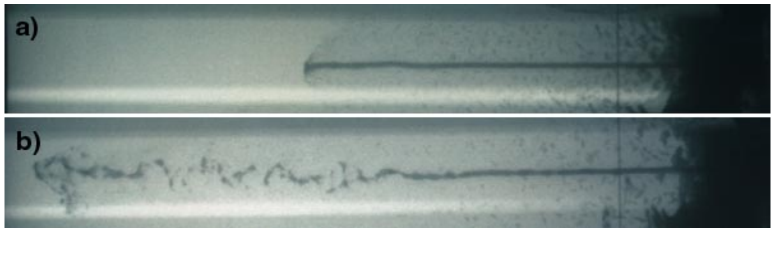

FIGURE 1. Radiographs of (a) an attenuated but unperturbed jet and (b) an attenuated and perturbed jet.

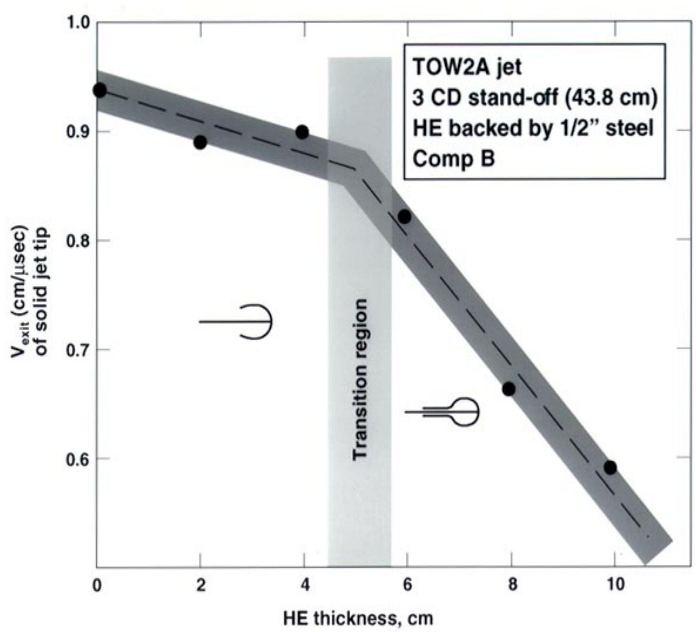

FIGURE 2. Exit velocity versus the HE thickness showing the transition between two types of flow.

has acquired a perpendicular velocity component in its passage through the HE, its ability to penetrate downstream targets has been seriously compromised. The part of the jet that can penetrate is the solid part. It is the trajectory of the tip of the solid jet that is predicted by the model described below.

The results of measuring the exit velocity of the solid jet tip as a function of the thickness of the HE target is shown in figure 2. The point at zero HE thickness was calculated. The other points are obtained from measurements. It is seen that the data is best fit by two lines; the intersection of the lines indicates the HE thickness where the effect of perturbations on the jet is becoming important. After that point, the exit velocity decreases rapidly with increasing HE thickness. For a stretching jet, which is a reasonable approximation to a TOW2A jet, the loss of exit velocity is a measure of the loss of jet.

PROPAGATION THROUGH THICK HE

In a second experiment, discussed previously [1], both TOW's and Vipers at a variety of stand-off distances penetrated different thickness of HE. In this case the HE was not backed by a steel plate, as in the experiment described above. The data for conditions such that the HE thickness exceeded 3 jet diameters is presented in figure 3. The exit velocity normalized to the incident velocity is plotted as a function of the HE thickness relative to the stand-off. It is noted that the penetration appears to scale with jet diameter, as one would expect. The results

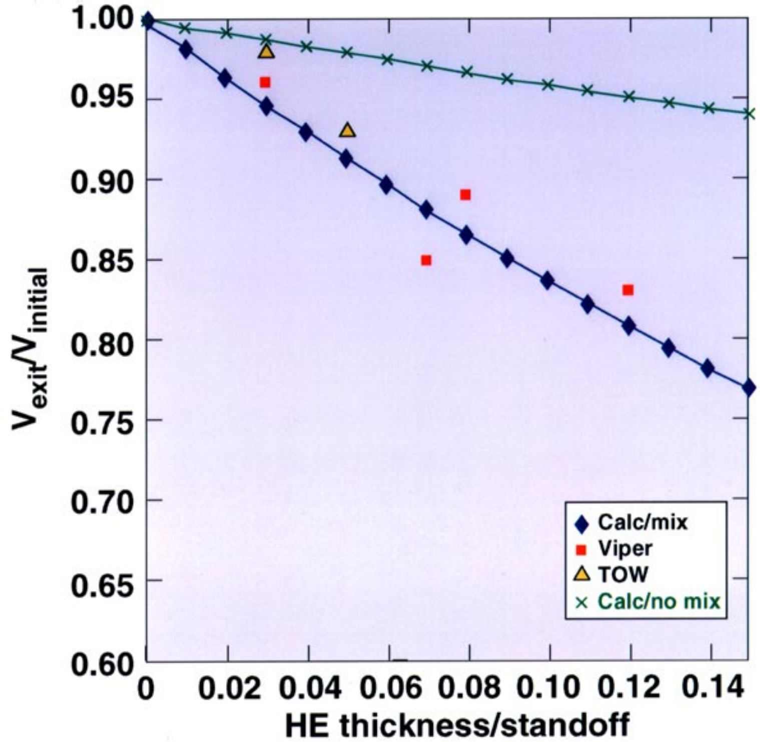

FIGURE 3. Exit velocity data for TOWs and Vipers compared with no-mix calculations and the model of this paper.

based on the model of [2, 3], which are similar to the results of hydrocode calculations, are shown. The curve for the model discussed below is fit to the data by the choice of the parameter F. The loss of jet, as indicated by the loss of jet exit velocity, exceeds that predicted by the model of [2, 3] and the hydrocode calculations and is substantial.

PROPAGATION THROUGH PRE-DETONATED HE

In a third experiment, a TOW2A jet penetrates explosive products. The explosive is detonated prior to arrival of the jet tip at the point where the jet tip would make contact on the explosive. Jet penetration data (position of the tip of the unperturbed jet and its velocity) was obtained as in the first experimental sequence above. The experimental arrangement was similar to that of the first sequence with the target HE having a thickness of 10 cm, and backed by a 1.3 cm steel plate. A detonator was placed on the explosive at the jet centerline. The results show that the jet is progressively less perturbed as the explosive is detonated at a greater time prior to the nominal time of impact of the jet of the front surface of the un-detonated explosive (figure 4). Our conclusion from this experiment and computational simulations is that it is the pressure in the detonation products that causes the excess attenuation of the jet.

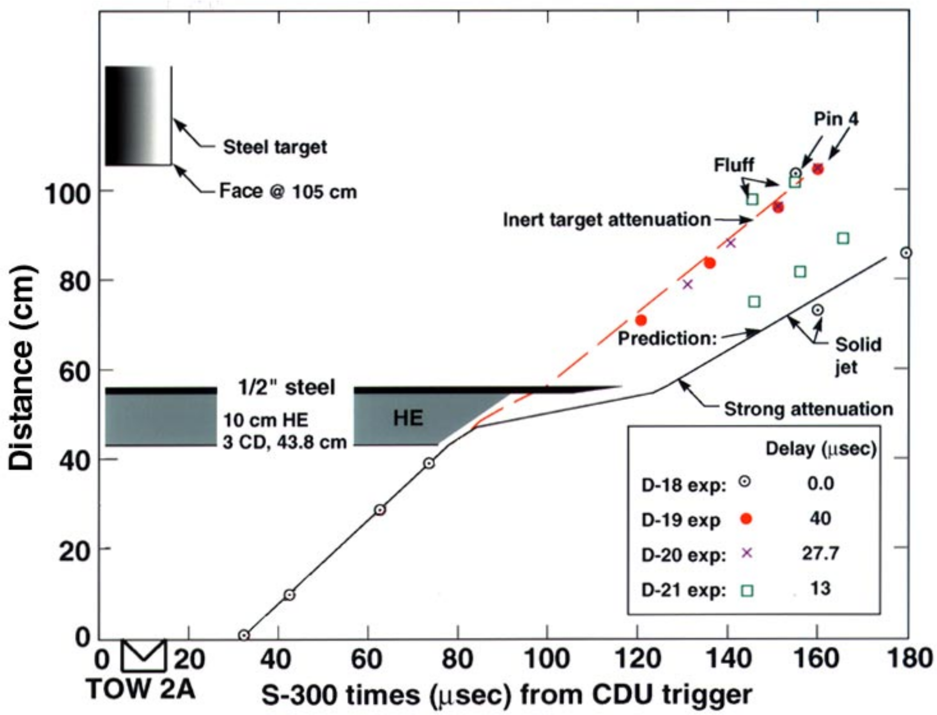

FIGURE 4. Calculated propagation of the tip of the solid jet tip (solid line) and the tip of the perturbed jet (dashed line). The data corresponds to the indicated pre-detonation times.

ANALYSIS OF THE JET / HE INTERACTION PROCESS

It is clear that there is a change in the flow pattern as the target is changes from thin to thick HE. Computations show that the most apparent change is in the jet material that has stagnated at the front of the jet and then flows counter to the incident jet. In the inert target, and for thin HE targets, the counter-flowing jet material flows more or less parallel to the incident jet as shown in the schematic of figure 5a. However, for thick HE targets, the pressure in the detonation products is sufficiently high and acts over a sufficient time that the counter-flowing jet material

(a) (b)

FIGURE 5. Schematic of jet flow configuration in (a) inert materials and thin HE, and (b) in thick HE after transition.

is forced onto the incident jet, resulting in both parallel and perpendicular momentum exchange with the jet. This flow pattern is illustrated in figure 5b. Mass exchange may take place as well and a Kelvin-Helmholz instability may grow. Once the jet is perturbed by acquiring a perpendicular velocity component, its ability to penetrate a downstream target is diminished.

A model which matches the data quite well consists of splitting the jet propagation through HE into two regions. In the first region, the jet enters the HE and propagates as though the HE were an inert material. The rate of propagation of the jet tip V_p is given by

$$V_p = V_{in} \ / \ (1+ \_\_ \qquad (1)$$

where V_{in} is the speed of the incoming jet, and _ is the square root of the density ratio $\__{HE} / \__{jet}$.

In this region the pressure of the detonation products does not materially affect the propagation of the jet. The extent of this region of flow can be calculated by a hydrocode and is limited by contact of the back-flowing jet material with the incoming jet. As the jet propagates, the back-flowing material is continually forced toward the incoming jet by the pressure in the detonation products. When the back-flowing material touches the incoming jet, the mixing and momentum transfer processes begin to take place. These processes are not well modeled by present hydrocodes for various reasons; until the codes become accurate, it is useful to use the present model to compute the rate of propagation of the jet.

The second region begins when the mixing processes are important; it is found that the jet propagation can be described by the speed of the front of the perturbed jet v_p and the speed of the front of the jet that is not significantly perturbed. It is useful to distinguish between these two parts of the jet because they differ in their ability to penetrate targets located beyond the HE. It is found experimentally that the perturbed jet will penetrate a target that is adjacent to the HE and 3 to 4 jet diameters thick. If the target is located tens of jet diameters downstream from the HE, there is no substantial penetration by the perturbed jet. The speed of the perturbed jet is well described by the above relation for V_p.

It is the front of the unperturbed, solid part of the jet that is of interest in modeling the penetration of targets located beyond the HE. It has been found that the speed of this jet front V_s in the HE can be modeled by the inclusion of a parameter F:

$$V_s = V_{in} \, (1\text{-}F) / (1+\_) \qquad (2)$$

where V_{in} is the speed of the incoming jet. F = 0.6 +/-0.1 for the available data.

For stretching jets, the speed ratio V_s / V_{in} is a function of the distance X from the source relative to the distance X_o from the source to the beginning of the region where the calculation is applicable.

$$V_s \ / \ V_{in} = (X \ / \ X_o)^{(\_+F) \ / \ (F-1)} \qquad (3)$$

X_o is the distance to the front of the explosive for the initial region where F = 0. For the region after the transition and within the explosive, F is finite and X_o is the distance to the transition. Similarly, V_{in} is the speed of the incoming jet at X_o.

This data discussed above is for Comp B and copper jets. F is dependent on the properties of the metal and the HE. More detailed studies of the model show that the value of the parameter F can be derived in different ways resulting in the same functional form, and hence additional data is required to further resolve the physical description of the processes and the dependence of F on the jet and HE properties. For relevant conditions, the formulation and value of F given here will accurately describe the penetration of a jet through HE.

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